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A Preliminary Measurement of the W Boson Mass using $W \to e\nu$ decays at DØ

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The preliminary measurement of the W boson mass from $e\nu$ decays produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the DØ detector for the 1994–1995 Fermilab run is presented. The analysis uses events with electrons in the central region ($|\eta| < 1.2$). From a sample of 32,856 W decay and 1562 dielectron events we measure the W mass to be $80.38 \pm 0.07(stat.) \pm 0.13(syst.) \pm 0.08(scale) GeV/c^2$. The technique for determining the mass and its systematic errors is discussed.

1 Introduction

The parameters of the electroweak sector of the Standard Model [1] can be taken to be the fine structure constant, the Fermi constant, and the mass of the Z boson, M_Z, all measured to a precision better than 0.01%. Higher order calculations then relate the mass of the W boson, M_W, and the weak mixing angle, θ_W, through these three parameters, the heavy fermion masses, and the Higgs boson mass. Within the Standard Model, a direct measurement of M_W thus constrains the allowed region for the top quark and Higgs masses. Alternatively, a precise measurement of the W mass in combination with measurements of $\sin^2\theta_W$ provides a test of the Standard Model. We present here the preliminary measurement based on the data collected with the DØ detector during the 1994–1995 run(Run 1b) at the Fermilab Tevatron collider. The 1992–1993 run(Run 1a) measurement has recently been submitted for publication [2].

Two components of the detector [3] are most relevant to this analysis. The central tracking system is used to reconstruct charged particle tracks and to reconstruct the vertices in the event. The calorimetry consists of one central and two end uranium liquid-argon calorimeters which measure the energy flow in the event over a pseudorapidity range $|\eta| \leq 4.2$.

Since the longitudinal component of the neutrino momentum is not measured, the W invariant mass cannot be reconstructed. This implies that the mass of the W boson must be extracted from some other kinematic distribution, such as the electron transverse energy, E_T^e, the neutrino transverse momentum, E_T^ν, or the transverse mass, defined as $m_T^2 = 2\,|\vec{E}_T^e|\,|\vec{E}_T^\nu|\,(1-\cos\varphi_{e\nu})$, where $\varphi_{e\nu}$ is the angle between the electron and neutrino transverse momenta. The m_T fit is used to extract the W mass since it has the greatest statistical power and is the least sensitive to certain systematic effects, notably the production model.

2 Event selection

Both $W \rightarrow e\nu$ and $Z \rightarrow ee$ decays are used in the analysis. The electrons from these decays tend to be isolated and of high transverse momentum. At the trigger level [4], W candidates were required to have an electromagnetic object with transverse energy $E_T \geq 20$ GeV and to have missing transverse energy $\not{E}_T \geq 15$ GeV, where $\not{E}_T = |\sum_{\mathrm{i}} \vec{E}_{\mathrm{i}} \sin\theta_{\mathrm{i}}|$, with the sum extending over all calorimeter cells. Z candidates were required to have two electromagnetic clusters, each with $E_T \geq 20$ GeV.

Each electron candidate was subjected to offline selection criteria to improve the sample purity. The transverse and longitudinal shower profile of the cluster were required to be consistent with that expected for an electron, based upon Monte Carlo simulations and test beam measurements [5]. The energy leakage of the cluster into the hadronic compartment of the calorimeter was required to be less than 10% of the cluster energy. Also, the cluster was required to be isolated. The total energy within a cone of radius $R = 0.4$, centered on the electron direction but outside the core of the shower with $R = 0.2$, was required to be less than 15% of the EM energy in the core. A spatial match of the cluster with a central detector track was required.

Fiducial criteria were also imposed to ensure that the electron candidates were well measured. Electron candidates with cluster position close to the end walls of the cryostat or close to the boundaries between the central calorimeter modules were eliminated from the data sample.

Having found events with well-identified, isolated electrons and, for W bosons, significant missing transverse energy, further kinematic constraints were imposed. The transverse energies of both electrons in Z events and the electron and neutrino in W events were required to exceed 25 GeV. The neutrino transverse energy was inferred from the total transverse energy balance and was equated to the missing transverse energy. In addition, the transverse momentum of the W boson, p_T^W, had to be less than 30 GeV/c.

3 Fast Monte Carlo model

The observed m_T distribution is used to extract M_W by a maximum likelihood fit. A fast Monte Carlo (MC) model is used to predict m_T spectra as a function of the W mass. These spectra provide the likelihood functions necessary for the fit. The fast MC model begins with a theoretical calculation of W or Z

production and decay at the 4–vector level. Relevant detector effects are simulated. These include the electron angle and energy response and resolutions, scale and resolution of the hadronic recoil system which balances the P_T of the W or Z, kinematic and fiducial acceptances, trigger and selection efficiencies and underlying event effects.

Only the most important features of the model are discussed. These include the modelling of the electron angle and energy and the transverse recoil vector. These correspond to the experimentally independent measurements. From these the neutrino transverse momentum is inferred.

3.1 Theoretical model

The starting point for the fast simulation is production of W or Z bosons according to a theoretical calculation [6] of $d^2\sigma/dp_T dy$ which includes a resummation of the leading divergences in $1/p_T^2$ as $p_T \rightarrow 0$. The calculation depends on parton distribution functions (pdf) and on a cutoff function S_{NP} which parametrizes non-perturbative physics at very small momenta. We use the MRSA pdf. S_{NP} has been parametrized and constrained using published Drell-Yan data from several experiments. The spectrum $d^2\sigma/dp_T dy$ determines the distributions of transverse and longitudinal momenta of the vector boson.

The mass of the W or Z is generated according to a relativistic Breit-Wigner lineshape with a skewing from the decrease of parton luminosity with increasing mass. The W width is fixed to its measured value, , $_W = (2.06 \pm 0.06)$ GeV/c^2 [4]. The decay products are generated with angular distributions respecting the boson polarization.

There are small correlation effects between the mass, P_T, rapidity and polarization of the W or Z boson due to parton luminosity effects. The effect of these correlations on the transverse mass fit has been checked with the RESBOS generator [7] and found to be small.

Radiative decays are generated according to the calculation of Berends and Kleiss [8]. For a fraction of the events $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$ decays are generated. With each simulated event there is also associated an event vertex position and an instantaneous luminosity which are used subsequently in the detector simulation.

The product of the theory stage of the simulation is a set of "true" 4-vectors which describe the event kinematics. The most important of these quantities are the true electron momentum and true recoil vectors, which when smeared and subjected to selection criteria, correspond to the quantities reconstructed in the detector and used to calculate the W transverse mass or Z invariant mass.

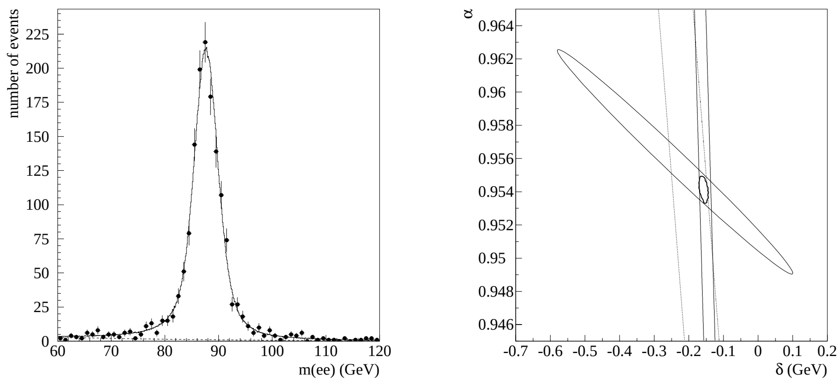


Figure 1: (Left) $Z \to ee$ invariant mass distribution. (Right) Constraints on slope α and offset δ from the observed $J/\psi \to e^+e^-$, $\pi^0 \to \gamma\gamma$, and $Z \to e^+e^-$ decays. The dark contour is the combined result.

The electron polar angle is computed from two points on the trajectory, the center of gravity of the calorimeter cluster and the center of gravity of the matched track in the central drift chamber. The calorimeter position finding algorithm was studied with test beam data and detailed Monte Carlo simulations. The central drift chamber has been calibrated using muons from both collider data and cosmic rays. The resolution of the polar angle is determined from $Z \to ee$ data. The two electron trajectories are extrapolated to the beam axis to give two independent estimates of the event vertex, z_1 and z_2. The polar angle resolution is then extracted from the distribution of the difference $z_1 - z_2$.

In modelling the electron energy response, we use the relationship between the energy measured in the calorimeter and the true energy $E_{\rm meas} = \alpha\, E_{\rm true} + \delta$. This relationship is derived from test beam studies. Two complementary approaches are used to constrain the energy scale α, and offset δ.

The first approach is based entirely on $Z \to ee$ decays and exploits the variation in energy of the electrons from $Z \to ee$ decays. The measured and true mass values are, to first order, related to each other by $m_{\rm meas} = \alpha\, m_{\rm true} + \delta\, f$. The variable f depends on the decay topology and is given by $f = \frac{2(E_1+E_2)}{m_{\rm true}} \sin^2 \gamma/2$, with γ the opening angle between the two decay products and E_1 and E_2 their energies. A fit to the Z mass as a function of f provides a measurement of both the scale and offset. Figure 1 shows the Z invariant mass spectrum and the allowed contour in the α–δ plane.

In the second approach, the Z resonance is used in conjunction with $\pi^0 \rightarrow \gamma\gamma$ and $J/\psi \rightarrow e^+e^-$ decays, and the precisely known masses of these three resonances. Both photons from a π^0 decay are required to convert so that we can measure the opening angle using the conversion tracks. However, the two photons are not resolved into separate clusters, so an invariant mass is not reconstructed. Instead we define the "symmetric mass," M_{sym}, to be the invariant mass computed as if the two photons had shared the cluster energy equally. The energy scale and offset are extracted by comparing the observed M_{sym} spectrum to a Monte Carlo simulation of the M_{sym} lineshape.

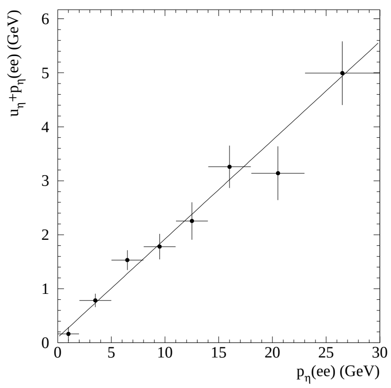
By combining the information from these methods we obtain an excellent constraint on the EM response. Figure 1 shows the constraints on the parameters α and δ from the π^0 data, the J/ψ data, and the complementary approach using just the Z events. When combined, these three independent constraints limit α and δ to the small elliptical region. Test beam measurements allows for a small nonlinear term in the energy response. Allowing such an additional term affects the determination of both the offset and the scale and alters the ratio of (M_W/M_Z) largely through the effect on δ. This has been included in the determination of the scale error. The dependence of the measured ratio of the W mass to Z mass on α and δ may be estimated from the equation

$$\left.\frac{M_W(\alpha,\delta)}{M_Z(\alpha,\delta)}\right|_{\text{meas}} = \left.\frac{M_W}{M_Z}\right|_{\text{true}} \left[1 + \frac{\delta}{\alpha} \cdot \frac{f_W\, M_Z - f_Z\, M_W}{M_Z \cdot M_W}\right] .$$

It should be noted that the W mass is insensitive to the energy scale α if δ is small. The offset results in a small correction to the measured mass. The uncertainty on the absolute energy scale results in an uncertainty on M_W of 80 MeV/c^2. The energy scale uncertainty is dominated by the limited statistical accuracy of the measured Z mass.

3.3 Recoil vector measurement and modelling

The relative response of the hadronic calorimeter with respect to the EM calorimeter is established by studying Z events. We denote this relative response α_{rec}. Figure 2 shows the imbalance between the P_T of the Z boson measured with the electrons, $\vec{P}_T^{ee}$, relative to the P_T measured with the hadronic system, $\vec{u}_T$. Both are projected onto the η axis, defined as the axis bisecting the transverse momentum vectors of the two electrons. This η–projection is used to minimize the effects of the electron resolutions. If the electron and hadron energy scales were the same this plot would be flat. A linear dependence is observed indicating a relative scale between the electron and hadron



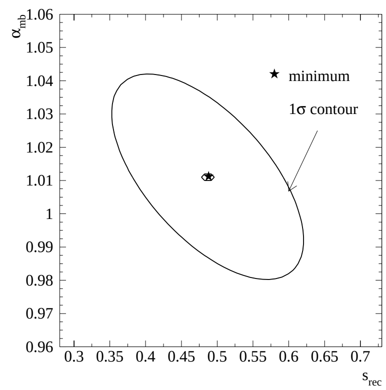


Figure 2: (Left)Comparison of P_T in $Z \to ee$ events measured with electrons and with the hadronic measurement. (Right)The allowed region for S_{rec} and α_{mb}.

measurements. The measured scale factor is (0.810 ± 0.015). To ensure an equivalent event topology between the W and Z events, Z decays in which one electron is in the end calorimeter were included in this study.

The measured recoil vector can be modelled as a sum of two components. The first is a vector parallel to the true boson P_T which is reconstructed with a scale α_{rec} relative to the EM scale. The second component is a vector symmetrically distributed with respect to the boson P_T direction. Intuitively, the first component corresponds to a recoil jet and the second to a resolution vector which combines the effects of the underlying event debris from spectator partons in the boson production interaction, calorimeter noise, particles from multiple interactions in the same beam crossing as the W or Z event and pileup effects from previous interactions. We model the asymmetric component by scaling the true P_T by a scale α_{rec} and applying a resolution with a constant term of 4% and a sampling term of S_{rec}. We model the symmetric component using collider minimum bias events with a luminosity distribution chosen so that the mean number of interactions is the same as the mean number of interactions in the W sample. We scale the $\vec{\not{E}}_T$ vector from the minimum bias events by a factor α_{mb}. We constrain the pair of parameters S_{rec} and α_{mb} by comparing the P_T measured with the electrons and the hadrons after correcting for the relative response of the electron and hadron measurements. The projection of that difference onto the η axis, $(\vec{P}_T^{ee} + \vec{P}_T^{rec}/\alpha_{rec}) \cdot \hat{\eta}$, is called the η balance. The width of the η balance is used to measure S_{rec} and α_{mb}.

Figure 2 shows the allowed values of the hadronic resolution parameters.

4 Detector and Reconstruction Biases

Detector and reconstruction biases were modelled in the Monte Carlo simulation. The energy underlying the electron was obtained from W events by measuring the energy deposited in a region of the calorimeter the same size as the electron cluster but rotated in azimuth. On average, the underlying event adds (16.7 ± 1.5) MeV per tower $(\Delta\eta \times \Delta\varphi = 0.1 \times 0.1)$ to the energy of central electrons.

The recoil system may affect the electron identification, especially if it is close to the electron. A measure of the event selection biases, through electron shape and isolation cuts, is obtained by studying the projection of the momentum recoiling against the W along the electron p_T direction $(\hat{p}_T^e)$: $u_{\parallel} \equiv \vec{p}_T^{\,rec} \cdot \hat{p}_T^e$. An inefficiency in $u_{\parallel}$ would cause a kinematic bias for the W decay products. Monte Carlo electrons simulated with GEANT were superimposed on events in the W sample, taking into account the appropriate kinematic correlations. The efficiency as a function of $u_{\parallel}$ was determined directly from this hybrid sample. The W mass from the transverse mass fit is largely insensitive to this inefficiency.

5 Backgrounds

The QCD jet background in the W sample was determined, from an independent jet data sample, to be $(1.5 \pm 0.3)\%$. The background from $Z \to e^+e^-$ events in which one electron is not identified has been estimated, using ISAJET [9], to be $\approx 0.5\%$. The irreducible background due to $W \to \tau\nu \to e\nu\nu\nu$ was included in the Monte Carlo simulation. All other sources of background are negligible.

6 W Mass Fit

The distribution in transverse mass and the Monte Carlo lineshape corresponding to the best fit to the data is shown in figure 3. The mass, extracted from a fit of the events in the range $60 \leq m_T \leq 90$ GeV/c^2, is $M_W = 80.38 \pm 0.07$ (stat.) GeV/c^2.

The χ^2 statistic is 87 for 59 degrees of freedom. The large value of χ^2 is due to four m_T bins with $|\chi| > 2.5$. These four points are scattered over the fitting window and there do not appear to be any systematic correlations between them. We have performed a Kolmogorov-Smirnov test to determine

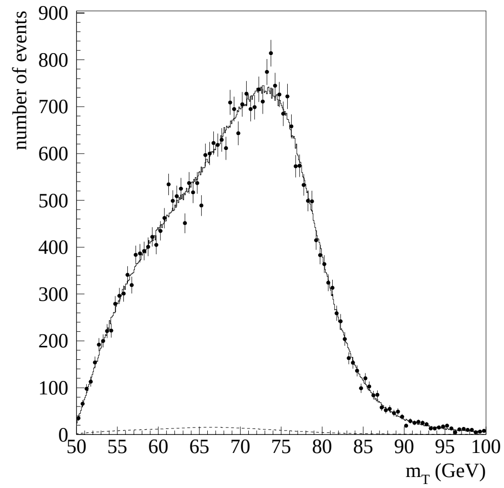


Figure 3: The transverse mass distribution for the W sample. The points indicate the data, the solid line the simulated m_T lineshape for the best fit, and the dashed line the background contribution.

the probability that the fit and the data come from the same parent distribution and obtain a probability of 95%. The fitted mass is insensitive to the choice of fitting window for a large range of values of both the upper and lower m_T limits. We conclude that the data m_T spectrum is well reproduced by the model.

7 Systematic errors

In general, systematic errors were estimated by varying the assumptions of the Monte Carlo model and determining the sensitivity of the W mass fit to each of the inputs to the model. For example, from the width of the $Z \rightarrow ee$ invariant mass distribution, the constant term in the electron energy resolution was measured to be $(0.9^{+0.30}_{-0.45})\%$. The systematic error due to the electron energy resolution is determined by evaluating the variation of the fitted mass over the allowed range of the energy resolution from this measurement. A similar procedure has been carried out for the various parameters used in the MC model and are listed in Table 1.

The data was collected over a wide range of instantaneous luminosities. A mass shift of 70 MeV/c^2 is observed when events collected at luminosities greater than $9 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are eliminated from the sample. We conservatively include a systematic error of 70 MeV/c^2 to account for possible inadequacies of the modelling of very high luminosity events. Extensive cross checks of the luminosity dependence incorporated into the fast Monte Carlo model are in progress, and it is anticipated that this uncertainty will be eliminated or reduced in the final result.

The error on M_W due to the P_T^W model and the pdfs is assigned the value evaluated for the Run 1a analysis [2]. This systematic error will be reduced with the analysis of the Run 1b data sample.

Table 1: Uncertainties in the W boson mass measurement.

Uncertainty	MeV/c^2
Statistical	70
Energy Scale	80
P_T^W, pdf	65
# of Min. Bias Events	40
Angle Calibration	40
Hadronic Energy Scale	30
EM Energy Resolution	30
Underlying Event	30
Hadronic Energy Resolution	20
Efficiencies	20
Radiative Decays	20
Backgrounds	15
W Natural Width	10
Calorimeter non-uniformity	10
Fit Error	5
Luminosity dependence	70
Total Systematic	130
Total	170

8 Conclusion

The preliminary measurement of the W boson mass extracted from the transverse mass spectrum of central $W \rightarrow e\nu$ decays for the 1994–1995 Fermilab Tevatron collider run is $M_W = 80.38 \pm 0.17$ GeV/c^2. Analysis to constrain the P_T^W model and the parton distribution functions is in progress. Also, the further study of the luminosity dependencies and uncertainties may reduce or eliminate the 70 MeV/c^2 error.

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